Parton shower matching and multijet merging at NLO

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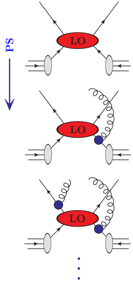
Institute for Particle Physics Phenomenology

LHCphenonet midterm meeting
Ravello, 20/09/2012

arXiv:1111.1220, arXiv:1201.5882
arXiv:1207.5030, arXiv:1207.5031
arXiv:1208.2815

Motivation



LO $pp \to 2$ with parton showers vs. **LO $pp \to n$ matrix elements**

+ exponentiation of large IR logarithms
− poor hard/wide angle emission pattern

+ dominant terms for hard/wide angle rad.
− breakdown of α_s-expansion in log. region

- MePs schemes: CKKW-type, MLM-type
  LO+(N)LL accuracy in every jet multiplicity
- scale setting scheme integral to preserve PS-resummation properties

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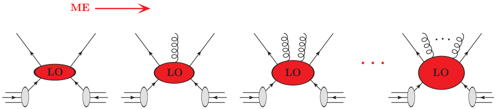

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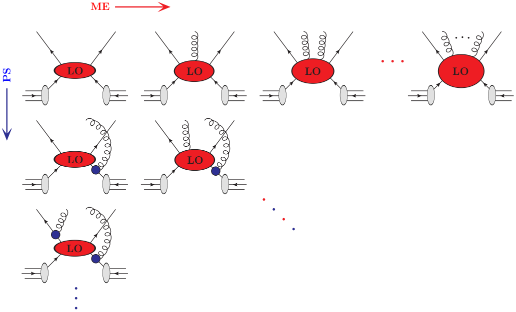

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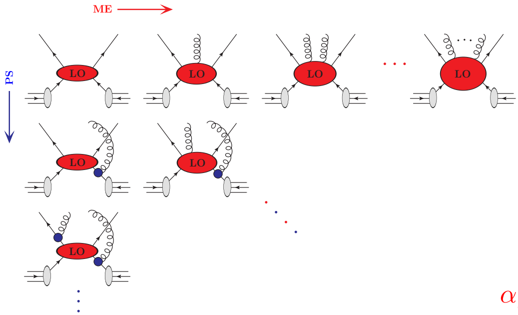

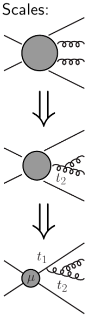

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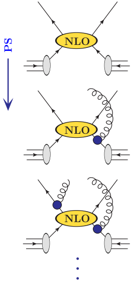

- promote LOPS to NLOPS (POWHEG, MC@NLO)
  $\rightarrow$ can assess uncertainties (part I)
- combine NLOPS for successive multiplicities into incl. sample (MEPS@NLO),
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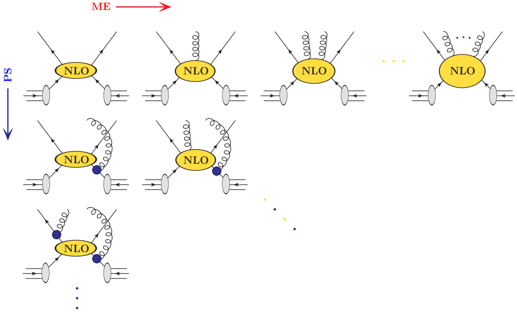

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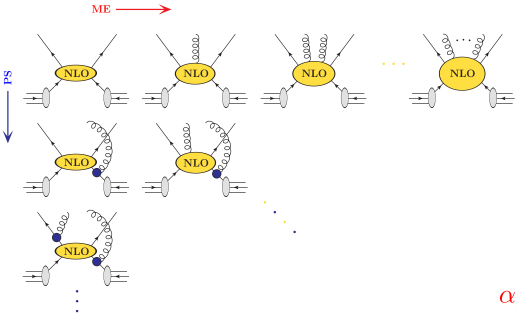

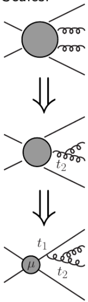

$$\alpha_s^{k+n}(\mu_{\text{eff}}) = \alpha_s^k(\mu)\,\alpha_s(t_1)\cdots\alpha_s(t_n)$$

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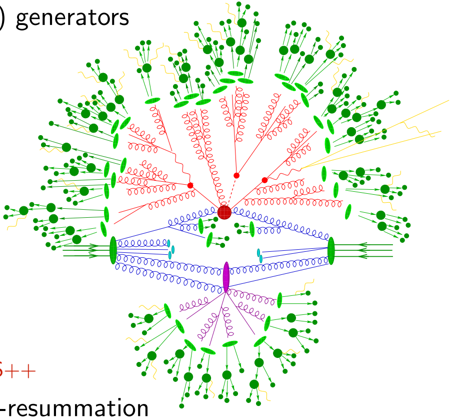
The SHERPA event generator framework



- Two multi-purpose Matrix Element (ME) generators
  AMEGIC++ JHEP02(2002)044
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Sherpa's traditional strength is the perturbative part of the event

MEPS (CKKW), MC@NLO, MENLOPS, MEPS@NLO

$\rightarrow$ full analytic control mandatory for consistency/accuracy

JHEP02(2009)007

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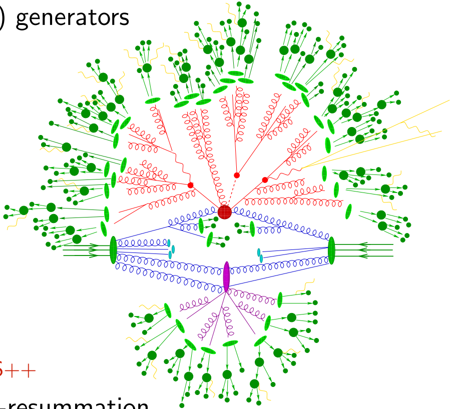

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Mc@Nlo

Frixione, Webber JHEP06(2002)029

$$\langle O\rangle^{\text{NLO+PS}} = \int \mathrm{d}\Phi_B\, \bar{\mathrm{B}}^{(\mathsf{A})}(\Phi_B)\Bigg[\Delta^{(\mathsf{A})}(t_0,\mu_Q^2)\,O(\Phi_B) + \int_{t_0}^{\mu_Q^2}\mathrm{d}\Phi_1\,\frac{\mathrm{D}^{(\mathsf{A})}(\Phi_B,\Phi_1)}{\mathrm{B}(\Phi_B)}\,\Delta^{(\mathsf{A})}(t,\mu_Q^2)\,O(\Phi_R)\Bigg] + \int \mathrm{d}\Phi_R\Big[\mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\mathsf{A})}(\Phi_R)\Big]\,O(\Phi_R)$$

Höche, Krauss, MS, Siegert arXiv:1111.1220

- NLO weighted Born configuration $\bar{\mathrm{B}}^{(\mathsf{A})} = \mathrm{B} + \tilde{\mathrm{V}} + \mathrm{I} + \int \mathrm{d}\Phi_1 [\mathrm{D}^{(\mathsf{A})} - \mathrm{D}^{(\mathsf{S})}]$
- use $\mathrm{D}_i^{(\mathsf{A})}$ as resummation kernels $\Delta^{(\mathsf{A})}(t,t') = \exp\left[\int_t^{t'} \mathrm{d}\Phi_1\, \mathrm{D}^{(\mathsf{A})}/\mathrm{B}\right]$
- resummation phase space limited by $\mu_Q^2 = t_{\text{max}}$
  $\rightarrow$ starting scale of parton shower evolution
  $\rightarrow$ should be of the order of the hard resummation scale
  $\Rightarrow$ **first implementation to allow to study μ_Q uncertainty**

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every term is well defined and NLO and NLL accuracy maintained if:

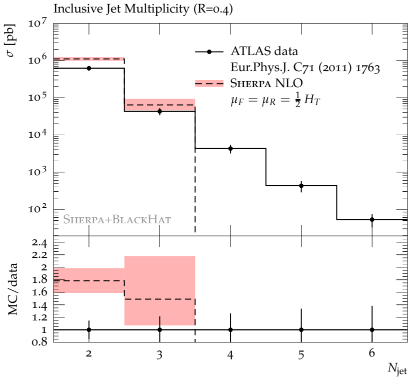
- $\mathrm{D}^{(\mathsf{A})} = \sum_i \mathrm{D}_i^{(\mathsf{A})}$ is full colour correct in soft limit
- $\mathrm{D}^{(\mathsf{A})} = \sum_i \mathrm{D}_i^{(\mathsf{A})}$ contains all spin correlations in collinear limit
- $\mathrm{D}_i^{(\mathsf{A})}$ and $\mathrm{D}_i^{(\mathsf{S})}$ have identical parton maps

$\Rightarrow$ **conventional parton showers need to be improved for that**

e.g. choose $\mathrm{D}_i^{(\mathsf{A})} = \mathrm{D}_i^{(\mathsf{S})}$ up to phase space constraints

Short-comings of fixed-order QCD

- poor description in phase space regions with strongly hierarchical scales
- poor perturbative jet-modeling (at most two constituents)
- no hadronisation, MPI effects
- very pronounced in inclusive & dijet production
- jet-$p_\perp$ turn negative in forward region unless y-dependent scale is used (e.g. $H_T^{(y)}$)



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≥ 2	$620 \pm 1.3^{+110}_{-66} \pm 24$	$958(1)^{+316}_{-221}$	$559(5)$	$1193(3)^{+130}_{-135}$	$0.95(0.02)$	$1130(19)^{+124}_{-129}$
≥ 3	$43 \pm 0.13^{+12}_{-6.2} \pm 1.7$	$93.4(0.1)^{+50.4}_{-30.3}$	$39.7(0.9)$	$54.5(0.5)^{+2.2}_{-19.9}$	$0.92(0.04)$	$50.2(2.1)^{+2.0}_{-18.3}$
≥ 4	$4.3 \pm 0.04^{+1.4}_{-0.79} \pm 0.24$	$9.98(0.01)^{+7.40}_{-3.95}$	$3.97(0.08)$	$5.54(0.12)^{+0.08}_{-2.44}$	$0.92(0.05)$	$5.11(0.29)^{+0.08}_{-2.32}$

Bern et.al. arXiv:1112.3940

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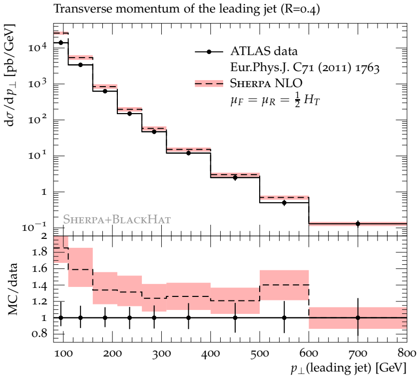

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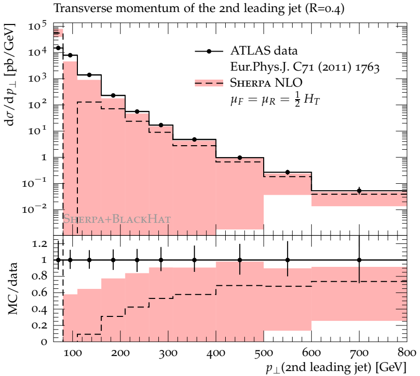

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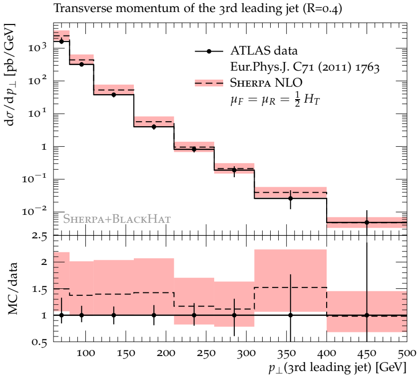

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Case study: Inclusive jet & dijet production

Describe wealth of experimental data with a single sample (LHC@7TeV)

Mc@Nlo di-jet production:

Höche, MS arXiv:1208.2815

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- hadron level calculation
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- virtual MEs from BlackHat
  Giele, Glover, Kosower Nucl.Phys.B403(1993)633-670
  Bern et.al. arXiv:1112.3940
- $p_\perp^{j_1} > 20$ GeV, $p_\perp^{j_2} > 10$ GeV

Uncertainty estimates:

- $\mu_{R/F} \in [\frac{1}{2}, 2]\,\mu_{R/F}^{\text{def}}$
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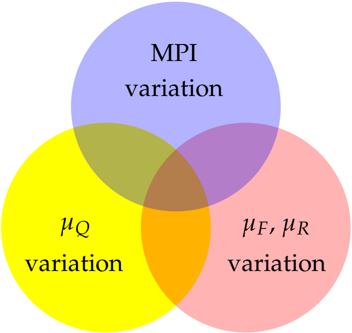
- MPI activity in tr. region $\pm$ 10%



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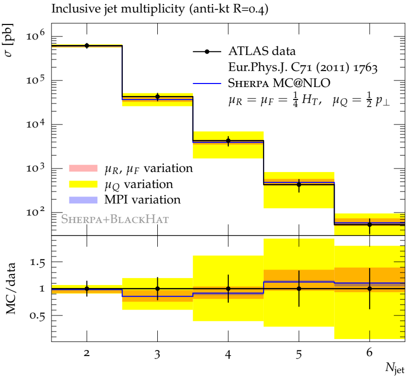

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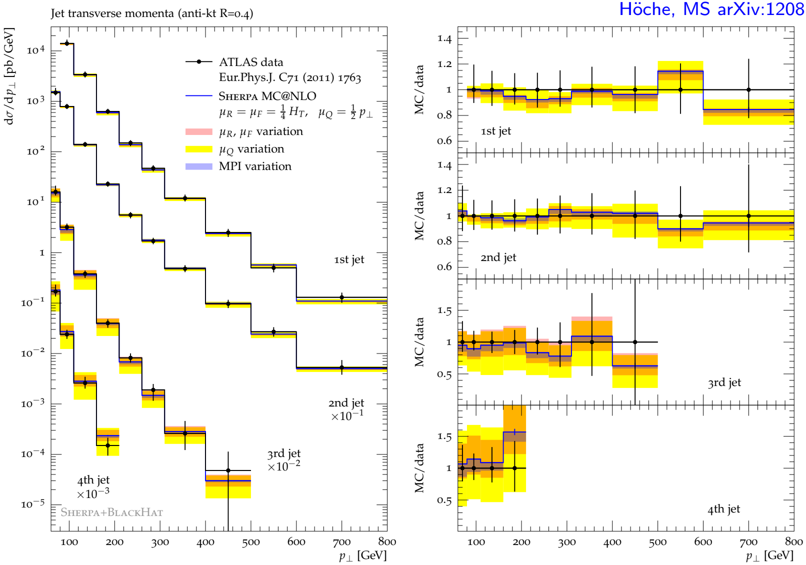

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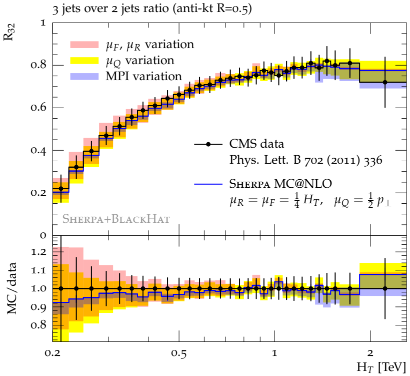

3-jet-over-2-jet ratio

- determined from incl. sample
  2-jet rate at NLO+NLL
  3-jet rate at LO+LL
- common scale choices
  → varied simultaneously
- at large H_T large MPI uncertainties
  → better MPI physics needed (soft QCD)
- similar description of related ATLAS observables

Case study: Inclusive jet & dijet production

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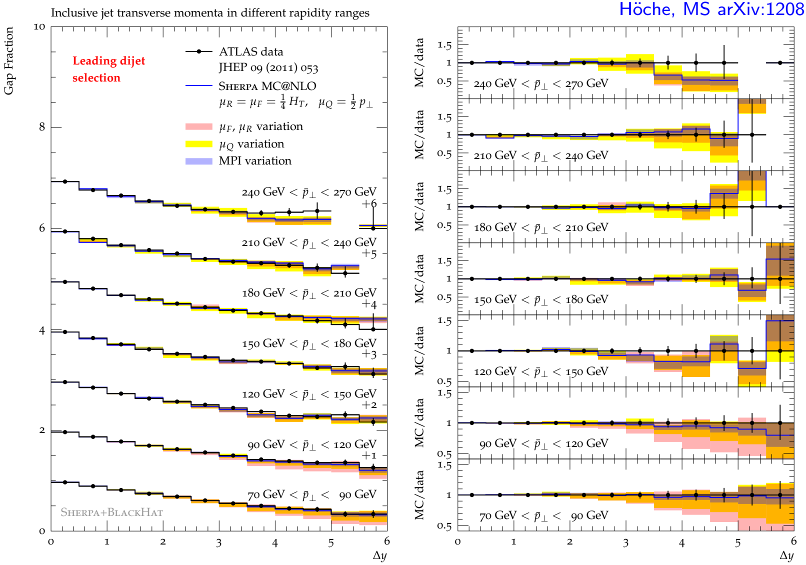

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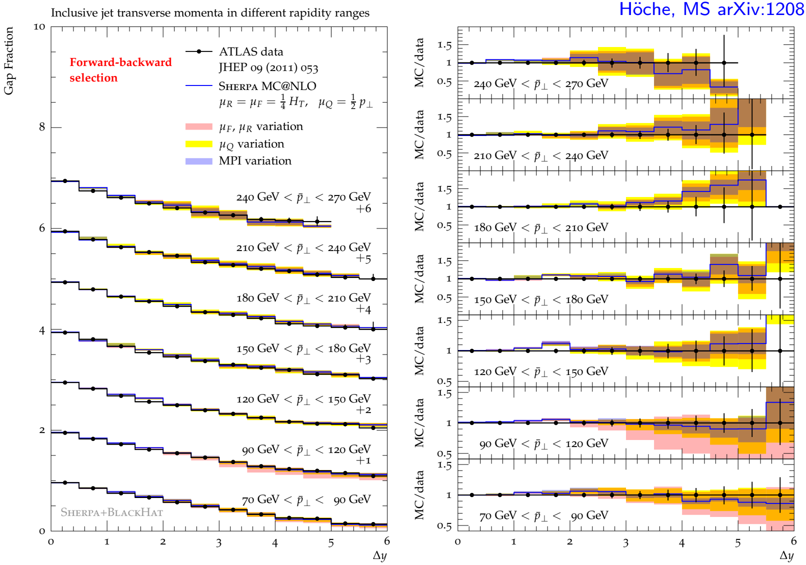


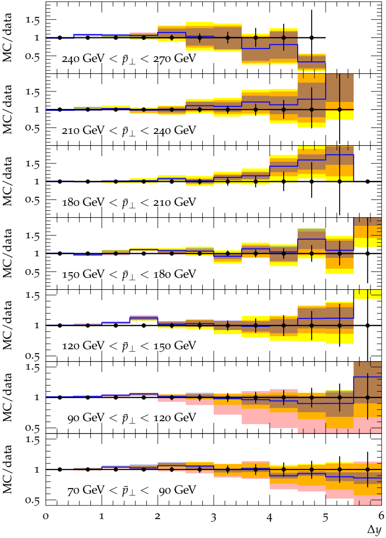
Case study: Inclusive jet & dijet production

- small-Δy region
  $\Rightarrow$ small uncertainty on additional jet production
- large-Δy region
  $\Rightarrow$ all uncertainties sizable

- small-$\bar{p}_\perp$ region
  $\Rightarrow$ dominated by perturbative uncertainties
- large-$\bar{p}_\perp$ region
  $\Rightarrow$ non-perturbative uncertainties as large as perturbative uncertainties

Reduction of theoretical uncertainty necessitates better understanding of soft QCD and non-factorisable contributions

Höche, MS arXiv:1208.2815



NLO merging

LO merging:

- LO accuracy for $n \leq n_{\mathsf{max}}$-jet processes
- preserve LL accuracy of the parton shower

Catani, Krauss, Kuhn, Webber JHEP11(2001)063

Lönnblad JHEP05(2002)046

Höche, Krauss, Schumann, Siegert JHEP05(2009)053

Hamilton, Richardson, Tully JHEP11(2009)038

Lönnblad, Prestel JHEP03(2012)019

NLO merging:

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Lavesson, Lönnblad JHEP12(2008)070

Höche, Krauss, MS, Siegert arXiv:1207.5030

Gehrmann, Höche, Krauss, MS, Siegert arXiv:1207.5031

NLO merging

Höche, Krauss, MS, Siegert arXiv:1207.5030

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$\langle O\rangle^{\text{MEPS@NLO}}$

$$
\begin{aligned}
&= \int \mathrm{d}\Phi_n\, \bar{\mathrm{B}}_n^{(\mathsf{A})} \Bigg[\Delta_n^{(\mathsf{A})}(t_0,\mu_Q^2)\, O_n \\
&\qquad\qquad + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_n^{(\mathsf{A})}}{\mathrm{B}_n}\, \Delta_n^{(\mathsf{A})}(t_{n+1},\mu_Q^2)\, \Theta(Q_{\text{cut}}-Q)\, O_{n+1}\Bigg] \\
&\quad + \int \mathrm{d}\Phi_{n+1} \left[\mathrm{R}_n - \mathrm{D}_n^{(\mathsf{A})}\right] \Theta(Q_{\text{cut}}-Q)\, \Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\, O_{n+1} \\
&\quad + \int \mathrm{d}\Phi_{n+1}\, \bar{\mathrm{B}}_{n+1}^{(\mathsf{A})}\, \Theta(Q-Q_{\text{cut}}) \\
&\qquad \times \left[\Delta_{n+1}^{(\mathsf{A})}(t_0,t_{n+1})\, O_{n+1} + \int_{t_0}^{t_{n+1}} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_{n+1}^{(\mathsf{A})}}{\mathrm{B}_{n+1}}\, \Delta_{n+1}^{(\mathsf{A})}(t_{n+2},t_{n+1})\, O_{n+2}\right] \\
&\quad + \int \mathrm{d}\Phi_{n+2} \left[\mathrm{R}_{n+1} - \mathrm{D}_{n+1}^{(\mathsf{A})}\right] \Theta(Q-Q_{\text{cut}})\, O_{n+2}
\end{aligned}
$$

NLO merging

Höche, Krauss, MS, Siegert arXiv:1207.5030
Gehrmann, Höche, Krauss, MS, Siegert arXiv:1207.5031

$\langle O\rangle^{\text{MePs@Nlo}}$

$$
\begin{aligned}
&= \int \mathrm{d}\Phi_n\; \bar{\mathrm{B}}_n^{(\mathsf{A})} \left[\Delta_n^{(\mathsf{A})}(t_0,\mu_Q^2)\, O_n \right.\\
&\qquad\left. + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_n^{(\mathsf{A})}}{\mathrm{B}_n}\, \Delta_n^{(\mathsf{A})}(t_{n+1},\mu_Q^2)\, \Theta(Q_{\mathsf{cut}}-Q)\, O_{n+1}\right]\\
&\quad + \int \mathrm{d}\Phi_{n+1} \left[\mathrm{R}_n - \mathrm{D}_n^{(\mathsf{A})}\right] \Theta(Q_{\mathsf{cut}}-Q)\; \Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\; O_{n+1}\\
&\quad + \int \mathrm{d}\Phi_{n+1}\; \bar{\mathrm{B}}_{n+1}^{(\mathsf{A})} \qquad \Theta(Q-Q_{\mathsf{cut}})\\
&\qquad \times \left[\Delta_{n+1}^{(\mathsf{A})}(t_0,t_{n+1})\, O_{n+1} + \int_{t_0}^{t_{n+1}} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_{n+1}^{(\mathsf{A})}}{\mathrm{B}_{n+1}}\, \Delta_{n+1}^{(\mathsf{A})}(t_{n+2},t_{n+1})\, O_{n+2}\right]\\
&\quad + \int \mathrm{d}\Phi_{n+2} \left[\mathrm{R}_{n+1} - \mathrm{D}_{n+1}^{(\mathsf{A})}\right] \Theta(Q-Q_{\mathsf{cut}})\, O_{n+2}
\end{aligned}
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NLO merging

Höche, Krauss, MS, Siegert arXiv:1207.5030

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$$
\begin{aligned}
\langle O\rangle^{\text{MEPS@NLO}}
&= \int \mathrm{d}\Phi_n\, \bar{\mathrm{B}}_n^{(\mathsf{A})} \bigg[\Delta_n^{(\mathsf{A})}(t_0,\mu_Q^2)\, O_n \\
&\qquad + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_n^{(\mathsf{A})}}{\mathrm{B}_n}\, \Delta_n^{(\mathsf{A})}(t_{n+1},\mu_Q^2)\, \Theta(Q_{\mathsf{cut}}-Q)\, O_{n+1} \bigg] \\
&\quad + \int \mathrm{d}\Phi_{n+1} \Big[\mathrm{R}_n - \mathrm{D}_n^{(\mathsf{A})}\Big]\, \Theta(Q_{\mathsf{cut}}-Q)\, \Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\, O_{n+1} \\
&\quad + \int \mathrm{d}\Phi_{n+1}\, \bar{\mathrm{B}}_{n+1}^{(\mathsf{A})} \qquad \Theta(Q - Q_{\mathsf{cut}}) \\
&\qquad \times \bigg[\Delta_{n+1}^{(\mathsf{A})}(t_0, t_{n+1})\, O_{n+1} + \int_{t_0}^{t_{n+1}} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_{n+1}^{(\mathsf{A})}}{\mathrm{B}_{n+1}}\, \Delta_{n+1}^{(\mathsf{A})}(t_{n+2}, t_{n+1})\, O_{n+2} \bigg] \\
&\quad + \int \mathrm{d}\Phi_{n+2} \Big[\mathrm{R}_{n+1} - \mathrm{D}_{n+1}^{(\mathsf{A})}\Big] \qquad \Theta(Q - Q_{\mathsf{cut}})\, O_{n+2}
\end{aligned}
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NLO merging

Höche, Krauss, MS, Siegert arXiv:1207.5030

Gehrmann, Höche, Krauss, MS, Siegert arXiv:1207.5031

$$
\begin{aligned}
\langle O\rangle^{\text{MePs@Nlo}}
&= \int \mathrm{d}\Phi_n\, \bar{\mathrm{B}}_n^{(\mathsf{A})}\bigg[\Delta_n^{(\mathsf{A})}(t_0,\mu_Q^2)\,O_n \\
&\qquad\qquad + \int_{t_0}^{\mu_Q^2}\mathrm{d}\Phi_1\,\frac{\mathrm{D}_n^{(\mathsf{A})}}{\mathrm{B}_n}\,\Delta_n^{(\mathsf{A})}(t_{n+1},\mu_Q^2)\,\Theta(Q_{\text{cut}}-Q)\,O_{n+1}\bigg] \\
&\quad + \int \mathrm{d}\Phi_{n+1}\Big[\mathrm{R}_n-\mathrm{D}_n^{(\mathsf{A})}\Big]\,\Theta(Q_{\text{cut}}-Q)\,\Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\,O_{n+1} \\
&\quad + \int \mathrm{d}\Phi_{n+1}\,\bar{\mathrm{B}}_{n+1}^{(\mathsf{A})}\bigg[1+\frac{\mathrm{B}_{n+1}}{\bar{\mathrm{B}}_{n+1}}\int_{t_{n+1}}^{\mu_Q^2}\mathrm{d}\Phi_1\,\mathrm{K}_n\bigg]\Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\,\Theta(Q-Q_{\text{cut}}) \\
&\qquad\qquad \times\bigg[\Delta_{n+1}^{(\mathsf{A})}(t_0,t_{n+1})\,O_{n+1}+\int_{t_0}^{t_{n+1}}\mathrm{d}\Phi_1\,\frac{\mathrm{D}_{n+1}^{(A)}}{\mathrm{B}_{n+1}}\,\Delta_{n+1}^{(\mathsf{A})}(t_{n+2},t_{n+1})\,O_{n+2}\bigg] \\
&\quad + \int \mathrm{d}\Phi_{n+2}\Big[\mathrm{R}_{n+1}-\mathrm{D}_{n+1}^{(\mathsf{A})}\Big]\,\Delta_{n+1}^{(\mathsf{PS})}(t_{n+2},t_{n+1})\,\Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\,\Theta(Q-Q_{\text{cut}})\,O_{n+2}
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&\quad + \int \mathrm{d}\Phi_{n+1}\, \bar{\mathrm{B}}_{n+1}^{(\mathsf{A})} \left[1 + \frac{\mathrm{B}_{n+1}}{\bar{\mathrm{B}}_{n+1}} \int_{t_{n+1}}^{\mu_Q^2} \mathrm{d}\Phi_1\, \mathrm{K}_n \right] \Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\text{cut}}) \\
&\qquad\qquad \times \left[\Delta_{n+1}^{(\mathsf{A})}(t_0,t_{n+1})\, O_{n+1} + \int_{t_0}^{t_{n+1}} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_{n+1}^{(A)}}{\mathrm{B}_{n+1}}\, \Delta_{n+1}^{(\mathsf{A})}(t_{n+2},t_{n+1})\, O_{n+2} \right] \\
&\quad + \int \mathrm{d}\Phi_{n+2} \Big[\mathrm{R}_{n+1} - \mathrm{D}_{n+1}^{(\mathsf{A})} \Big]\, \Delta_{n+1}^{(\mathsf{PS})}(t_{n+2},t_{n+1})\, \Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\text{cut}})\, O_{n+2}
\end{aligned}
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NLO merging

Höche, Krauss, MS, Siegert arXiv:1207.5030

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$$
\begin{aligned}
\langle O\rangle^{\text{MEPS@NLO}}
&= \int \mathrm{d}\Phi_n\, \bar{\mathrm{B}}_n^{(\mathsf{A})} \Bigg[\Delta_n^{(\mathsf{A})}(t_0,\mu_Q^2)\, O_n \\
&\qquad + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_n^{(\mathsf{A})}}{\mathrm{B}_n}\, \Delta_n^{(\mathsf{A})}(t_{n+1},\mu_Q^2)\, \Theta(Q_{\text{cut}}-Q)\, O_{n+1}\Bigg] \\
&\quad + \int \mathrm{d}\Phi_{n+1} \left[\mathrm{R}_n - \mathrm{D}_n^{(\mathsf{A})}\right] \Theta(Q_{\text{cut}}-Q)\, \Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\, O_{n+1} \\
&\quad + \int \mathrm{d}\Phi_{n+1}\, \bar{\mathrm{B}}_{n+1}^{(\mathsf{A})} \left[1 + \frac{\mathrm{B}_{n+1}}{\bar{\mathrm{B}}_{n+1}} \int_{t_{n+1}}^{\mu_Q^2} \mathrm{d}\Phi_1\, \mathrm{K}_n\right] \Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\text{cut}}) \\
&\qquad \times \left[\Delta_{n+1}^{(\mathsf{A})}(t_0,t_{n+1})\, O_{n+1} + \int_{t_0}^{t_{n+1}} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_{n+1}^{(A)}}{\mathrm{B}_{n+1}}\, \Delta_{n+1}^{(\mathsf{A})}(t_{n+2},t_{n+1})\, O_{n+2}\right] \\
&\quad + \int \mathrm{d}\Phi_{n+2} \left[\mathrm{R}_{n+1} - \mathrm{D}_{n+1}^{(\mathsf{A})}\right] \Delta_{n+1}^{(\mathsf{PS})}(t_{n+2},t_{n+1})\, \Delta_n^{(\mathsf{PS})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\text{cut}})\, O_{n+2}
\end{aligned}
$$

NLO merging

Höche, Krauss, MS, Siegert arXiv:1207.5030
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$$
\begin{aligned}
\langle O\rangle^{\text{MEPS@NLO}}
&= \int \mathrm{d}\Phi_n\, \bar{\mathrm{B}}_n^{(\mathrm{A})} \Bigg[\Delta_n^{(\mathrm{A})}(t_0,\mu_Q^2)\, O_n \\
&\qquad\qquad + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_n^{(\mathrm{A})}}{\mathrm{B}_n}\, \Delta_n^{(\mathrm{A})}(t_{n+1},\mu_Q^2)\, \Theta(Q_{\text{cut}}-Q)\, O_{n+1}\Bigg] \\
&\quad + \int \mathrm{d}\Phi_{n+1} \left[\mathrm{R}_n - \mathrm{D}_n^{(\mathrm{A})}\right] \Theta(Q_{\text{cut}}-Q)\, \Delta_n^{(\mathrm{PS})}(t_{n+1},\mu_Q^2)\, O_{n+1} \\
&\quad + \int \mathrm{d}\Phi_{n+1}\, \bar{\mathrm{B}}_{n+1}^{(\mathrm{A})} \left[1 + \frac{\mathrm{B}_{n+1}}{\bar{\mathrm{B}}_{n+1}} \int_{t_{n+1}}^{\mu_Q^2} \mathrm{d}\Phi_1\, \mathrm{K}_n\right] \Delta_n^{(\mathrm{PS})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\text{cut}}) \\
&\qquad\qquad \times \left[\Delta_{n+1}^{(\mathrm{A})}(t_0,t_{n+1})\, O_{n+1} + \int_{t_0}^{t_{n+1}} \mathrm{d}\Phi_1\, \frac{\mathrm{D}_{n+1}^{(A)}}{\mathrm{B}_{n+1}}\, \Delta_{n+1}^{(\mathrm{A})}(t_{n+2},t_{n+1})\, O_{n+2}\right] \\
&\quad + \int \mathrm{d}\Phi_{n+2} \left[\mathrm{R}_{n+1} - \mathrm{D}_{n+1}^{(\mathrm{A})}\right] \Delta_{n+1}^{(\mathrm{PS})}(t_{n+2},t_{n+1})\, \Delta_n^{(\mathrm{PS})}(t_{n+1},\mu_Q^2)\, \Theta(Q-Q_{\text{cut}})\, O_{n+2}
\end{aligned}
$$

NLO merging – Generation of MC counterterm

$$\left[1 + \frac{\mathrm{B}_{n+1}}{\bar{\mathrm{B}}_{n+1}} \int_{t_{n+1}}^{\mu_Q^2} \mathrm{d}\Phi_1\, \mathrm{K}_n\right]$$

- same form as exponent of Sudakov form factor $\Delta_n^{(\mathsf{PS})}(t_{n+1}, \mu_Q^2)$
- truncated parton shower on n-parton configuration underlying $n+1$-parton event
  1. no emission $\rightarrow$ retain $n+1$-parton event as is
  2. first emission at t' with $Q > Q_{\mathsf{cut}}$, multiply event weight with $\mathrm{B}_{n+1}/\bar{\mathrm{B}}_{n+1}^{(\mathsf{A})}$, restart evolution at t', do not apply emission kinematics
  3. treat every subsequent emission as in standard truncated vetoed shower
- generates

$$\left[1 + \frac{\mathrm{B}_{n+1}}{\bar{\mathrm{B}}_{n+1}} \int_{t_{n+1}}^{\mu_Q^2} \mathrm{d}\Phi_1\, \mathrm{K}_n\right] \Delta_n^{(\mathsf{PS})}(t_{n+1}, \mu_Q^2)$$

$\Rightarrow$ **identify $\mathcal{O}(\alpha_s)$ counterterm with the emitted emission**

NLO merging

Renormalisation scales:

- determined by clustering using PS probabilities and taking the respective nodal values t_i

$$\alpha_s(\mu_R^2)^k = \prod_{i=1}^{k} \alpha_s(t_i)$$

- change of scales $\mu_R \to \tilde{\mu}_R$ in MEs necessitates one-loop counter term

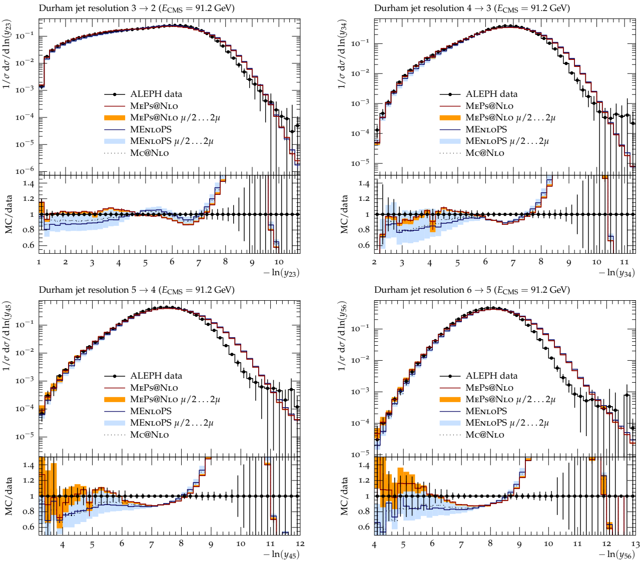
$$\alpha_s(\tilde{\mu}_R^2)^k \left(1 - \frac{\alpha_s(\tilde{\mu}_R^2)}{2\pi}\,\beta_0 \sum_{i=1}^{k} \ln \frac{t_i}{\tilde{\mu}_R^2}\right)$$

Factorisation scale:

- μ_F determined from core n-jet process
- change of scales $\mu_F \to \tilde{\mu}_F$ in MEs necessitates one-loop counter term

$$\mathrm{B}_n(\Phi_n)\,\frac{\alpha_s(\tilde{\mu}_R^2)}{2\pi}\,\log\frac{\mu_F^2}{\tilde{\mu}_F^2}\left(\sum_{c=q,g}^{n}\int_{x_a}^{1}\frac{\mathrm{d}z}{z}\,P_{ac}(z)\,f_c(x_a/z,\tilde{\mu}_F^2) + \ldots\right)$$

Results: $e^+e^- \to$ hadrons



$ee \to$ hadrons (2,3,4 @ NLO; 5,6 @ LO)

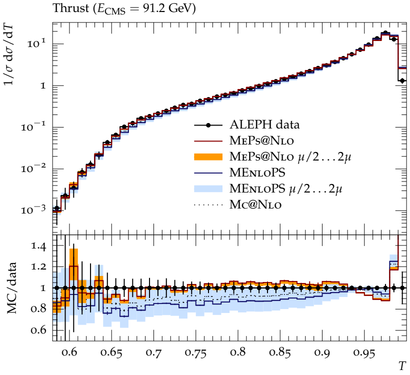
Jet resolutions (Durham measure)

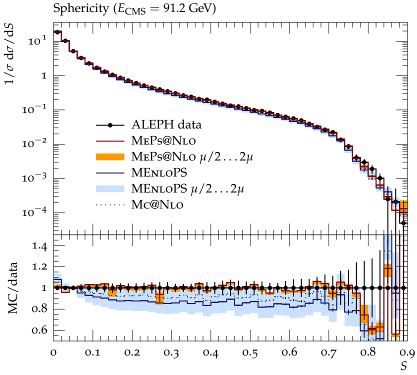
- MEPS@NLO vs MENLOPS
- at $y \ll 1$ dominated by hadr. effects $\to$ needs retuning
- much improved ren. scale dependence

ALEPH data
EPJC35(2004)457-486

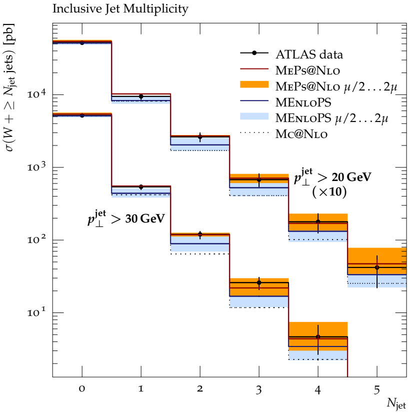
Results: $e^+e^- \to$ hadrons

ALEPH data EPJC35(2004)457-486





Results: pp $\to$ W+jets

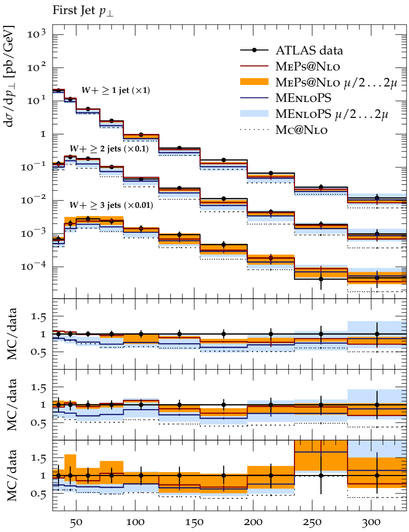


$pp \to W$+jets (0,1,2 @ NLO; 3,4 @ LO)

- $\mu_{R/F} \in [\frac{1}{2}, 2]\,\mu_{\mathrm{def}}$ scale uncertainty much reduced
- NLO dependece for $pp \to W$+0,1,2 jets LO dependence for $pp \to W$+3,4 jets
- $Q_{\mathrm{cut}} = 30$ GeV
- good data description

ATLAS data Phys.Rev.D85(2012)092002

Results: pp → W+jets



$pp \to W+$jets (0,1,2 @ NLO; 3,4 @ LO)

- $\mu_{R/F} \in [\frac{1}{2}, 2]\,\mu_{\text{def}}$
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ATLAS data Phys.Rev.D85(2012)092002

Results: pp → W+jets

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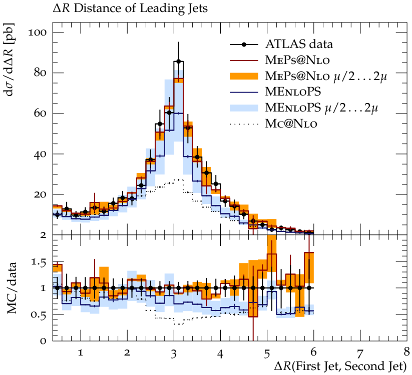
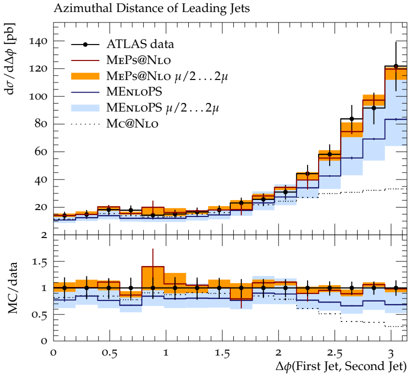




Conclusions

- SHERPA's MC@NLO formulation allows full evaluation of perturbative uncertainties (μ_F, μ_R, μ_Q)
- MC@NLO can be easily combined with MEPS $\rightarrow$ MENLOPS
- MC@NLO is a necessary input for NLO merging $\rightarrow$ MEPS@NLO
- MEPS@NLO gives full benefits of NLO calculations (scale dependences, normalisations) while also retaining full (N)LL accuracy of parton shower

$\Rightarrow$ will be included in next major release

Current release: SHERPA-1.4.1

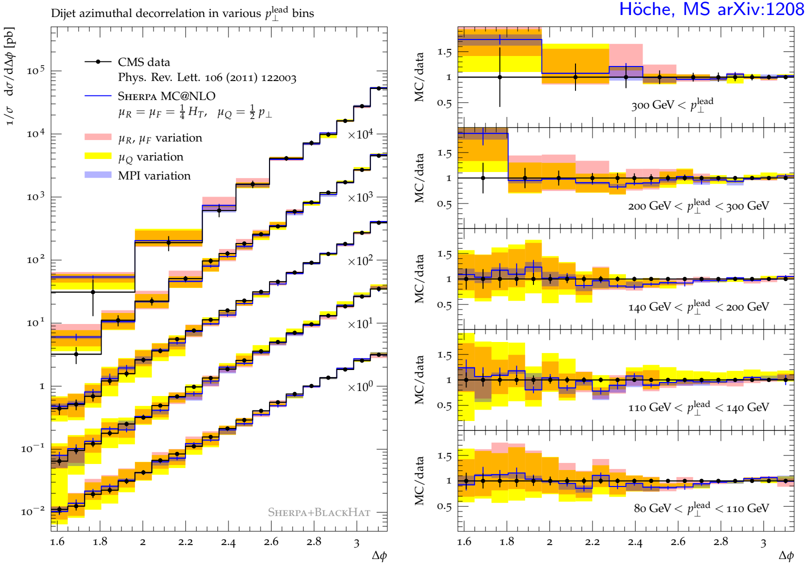
http://sherpa.hepforge.org

- better description of perturbative QCD is only part of the story to achieve higher precission for (hard) collider observables

Thank you for your attention!

Case study: Inclusive jet & dijet production

Höche, MS arXiv:1208.2815



Case study: Inclusive jet & dijet production

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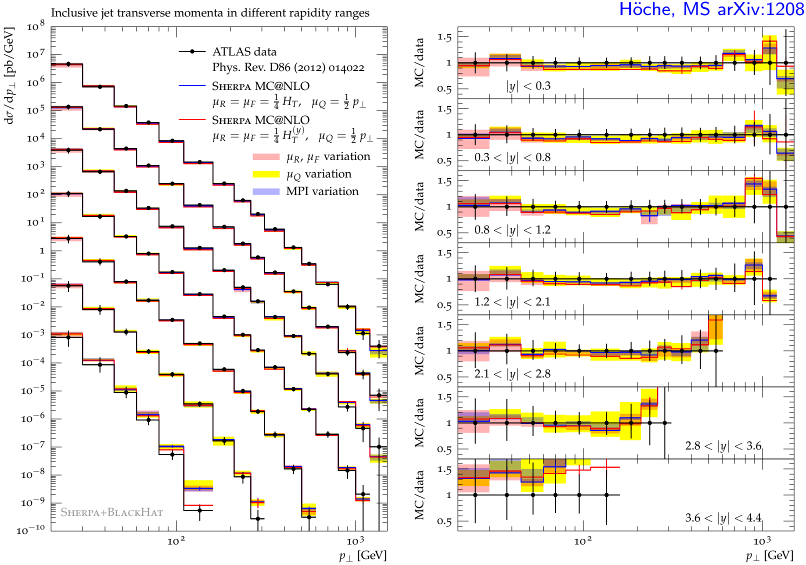

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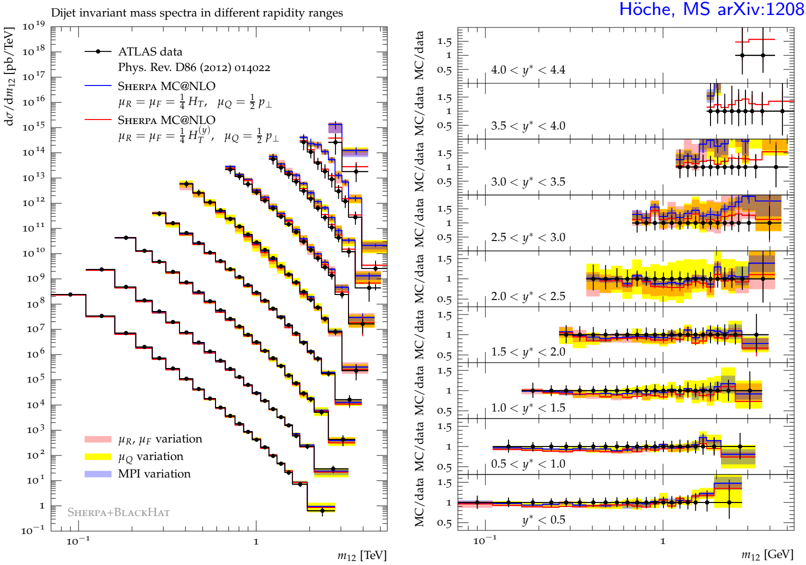


Case study: Inclusive jet & dijet production

Höche, MS arXiv:1208.2815

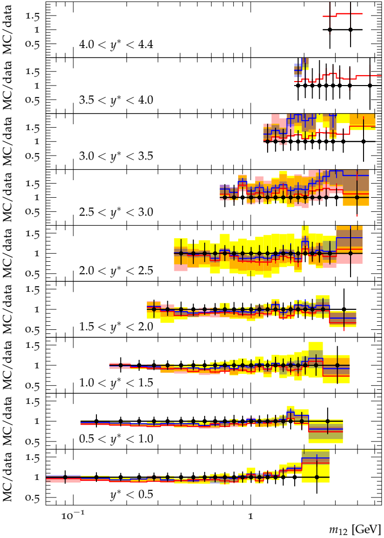
Try different scale

- $\mu_{R/F} = \frac{1}{4}\, H_T^{(y)}$ with $H_T^{(y)} = \sum_{i\in\text{jets}} p_{\perp,i}\, e^{0.3|y_\text{boost}-y_i|}$ with $y_\text{boost} = 1/n_\text{jets} \sum_{i\in\text{jets}} y_i$
- reduces to $\mu_{R/F} = \frac{1}{2}\, p_\perp\, e^{0.3y^*}$ with $y^* = \frac{1}{2}|y_1 - y_2|$ for $2 \to 2$ and captures real emission dynamics

  Ellis, Kunszt, Soper PRD40(1989)2188
- better description of data at large rapidities, as expected

description of most other observables worsened

need proper description of forward physics (e.g. (B)FKL)



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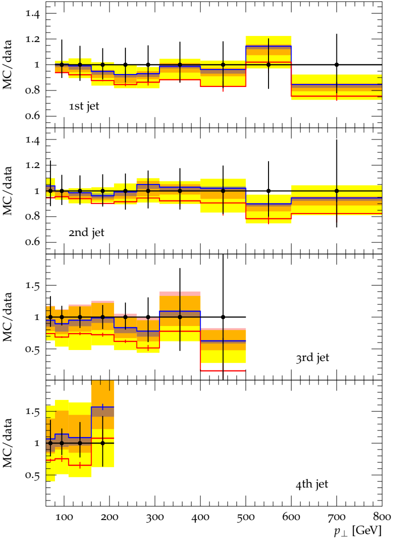

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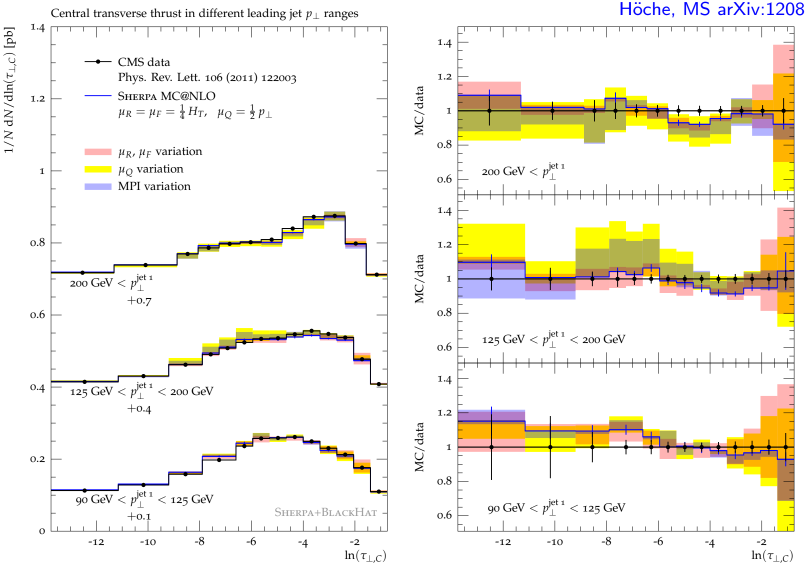

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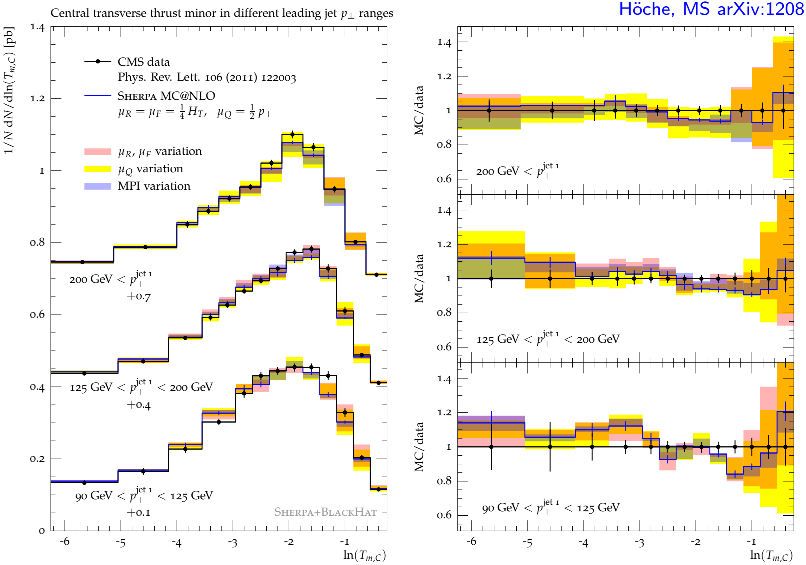
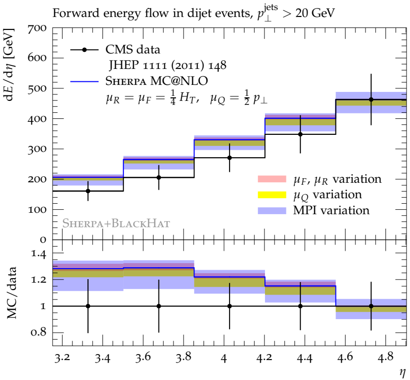


Case study: Inclusive jet & dijet production



Höche, MS arXiv:1208.2815

Forward energy flow

- energy flow in rapidity interval per event with a central back-to-back di-jet pair
- normalisation reduces $\mu_{R/F}$ and μ_Q dependence
- dominated by MPI modeling uncertainty

General NLO calculations

- NLO calculation with subtraction methods

$$\langle O\rangle^{\textsf{NLO}} = \int \mathrm{d}\Phi_B \Big[\mathrm{B}(\Phi_B) + \mathrm{V}(\Phi_B) + \mathrm{I}(\Phi_B)\Big]\, O(\Phi_B)$$

$$+ \int \mathrm{d}\Phi_R \Big[\qquad - \sum_i \mathrm{D}_i^{(\mathsf{S})}(\Phi_R) \qquad O(\Phi_{B_i})\Big]$$

$$+ \int \mathrm{d}\Phi_R \Big[\mathrm{R}(\Phi_R) \qquad \Big]\, O(\Phi_R)$$

- introduce second set of subtraction functions $\mathrm{D}_i^{(\mathsf{A})}$
- $\mathrm{D}_i^{(\mathsf{A})}$ and $\mathrm{D}_i^{(\mathsf{S})}$ need to have same momentum maps and IR limit

General NLO calculations

- NLO calculation with subtraction methods

$$\langle O\rangle^{\text{NLO}} = \int \mathrm{d}\Phi_B \Big[\mathrm{B}(\Phi_B) + \mathrm{V}(\Phi_B) + \mathrm{I}(\Phi_B)\Big]\, O(\Phi_B)$$

$$+ \int \mathrm{d}\Phi_R \quad \Big[\sum_i \mathrm{D}_i^{(\mathsf{A})}(\Phi_R) \quad O(\Phi_{B_i}) - \sum_i \mathrm{D}_i^{(\mathsf{S})}(\Phi_R) \quad O(\Phi_{B_i})\Big]$$

$$+ \int \mathrm{d}\Phi_R \Big[\mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\mathsf{A})}(\Phi_R)\Big]\, O(\Phi_R) + \langle O\rangle^{(\mathsf{A})}_{\mathsf{corr}}$$

$$\langle O\rangle^{(\mathsf{A})}_{\mathsf{corr}} = \int \mathrm{d}\Phi_R \sum\nolimits_i \mathrm{D}_i^{(\mathsf{A})} \big[O(\Phi_R) - O(\Phi_{B_i})\big]$$

- introduce second set of subtraction functions $\mathrm{D}_i^{(\mathsf{A})}$
- $\mathrm{D}_i^{(\mathsf{A})}$ and $\mathrm{D}_i^{(\mathsf{S})}$ need to have same momentum maps and IR limit

General NLO calculations

- NLO calculation with subtraction methods

$$\begin{aligned}\langle O\rangle^{\mathsf{NLO}} = & \int \mathrm{d}\Phi_B \Big[\mathrm{B}(\Phi_B) + \mathrm{V}(\Phi_B) + \mathrm{I}(\Phi_B)\Big]\, O(\Phi_B) \\ & + \sum_i \int \mathrm{d}\Phi_R \Big[\mathrm{D}_i^{(\mathsf{A})}(\Phi_R) - \mathrm{D}_i^{(\mathsf{S})}(\Phi_R)\Big]\, O(\Phi_{B_i}) \\ & + \int \mathrm{d}\Phi_R \Big[\mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\mathsf{A})}(\Phi_R)\Big]\, O(\Phi_R) + \langle O\rangle^{(\mathsf{A})}_{\mathsf{corr}}\end{aligned}$$

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$$\begin{aligned}\langle O\rangle^{\mathsf{NLO}} =& \int \mathrm{d}\Phi_B \Big[\mathrm{B}(\Phi_B) + \mathrm{V}(\Phi_B) + \mathrm{I}(\Phi_B)\Big]\, O(\Phi_B) \\ &+ \sum_i \int \mathrm{d}\Phi_{B_i} \mathrm{d}\Phi_1^i \Big[\mathrm{D}_i^{(\mathsf{A})}(\Phi_{B_i}, \Phi_1^i) - \mathrm{D}_i^{(\mathsf{S})}(\Phi_{B_i}, \Phi_1^i)\Big]\, O(\Phi_{B_i}) \\ &+ \int \mathrm{d}\Phi_R \Big[\mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\mathsf{A})}(\Phi_R)\Big]\, O(\Phi_R) + \langle O\rangle_{\mathsf{corr}}^{(\mathsf{A})}\end{aligned}$$

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$$\langle O\rangle^{\text{NLO}} = \int \mathrm{d}\Phi_B \;\; \bar{\mathrm{B}}^{(\text{A})}(\Phi_B)\;\; O(\Phi_B)$$

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Parton showers and resummation

- parton shower/resummation kernel $\mathcal{K}_i(\Phi_1)$, $\Phi_1 = \{t, z, \phi\}$
  $\to \mathcal{K}_i$ incorporates divergent propagator and DGLAP splitting kernels

$$\langle O\rangle^{\text{PS}} = \int \mathrm{d}\Phi_B\, \mathrm{B}(\Phi_B)\, O(\Phi_B)$$

$$= \int \mathrm{d}\Phi_B\, \mathrm{B}(\Phi_B)\, O(\Phi_B) +$$

- Sudakov form factor $\Delta^{(\mathcal{K})}(t,t') = \exp\left[-\int_t^{t'} \mathrm{d}\Phi_1\, \mathcal{K}(\Phi_1)\right]$ contains resummation features
- $\langle O\rangle^{(\mathcal{K})}_{\text{corr}}$ generated by one parton shower step

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$$= \int \mathrm{d}\Phi_B\,\mathrm{B}(\Phi_B)\,O(\Phi_B) +$$

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$$= \int \mathrm{d}\Phi_B\,\mathrm{B}(\Phi_B)\,O(\Phi_B) + \int\limits_{t_0}^{\mu_F^2} \mathrm{d}\Phi_R\,\mathrm{B}\cdot\mathcal{K}(\Phi_1)\Big[O(\Phi_R) - O(\Phi_B)\Big] + \mathcal{O}(\alpha_s^2)$$

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General NLO+PS matching

$$\langle O\rangle^{\text{NLO+PS}} = \int \mathrm{d}\Phi_B\, \bar{\mathrm{B}}^{(\mathrm{A})}(\Phi_B)\left[\Delta^{(\mathrm{A})}(t_0,\mu_Q^2)\, O(\Phi_B) + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathrm{D}^{(\mathrm{A})}(\Phi_B,\Phi_1)}{\mathrm{B}(\Phi_B)}\, \Delta^{(\mathrm{A})}(t,\mu_Q^2)\, O(\Phi_R)\right]$$

$$+ \int \mathrm{d}\Phi_R\left[\mathrm{R}(\Phi_R) - \sum_i \mathrm{D}_i^{(\mathrm{A})}(\Phi_R)\right] O(\Phi_R) + \langle O\rangle^{(\mathrm{A})}_{\text{corr}}$$

- use $\mathrm{D}_i^{(\mathrm{A})}$ as resummation kernels
- resummation phase space limited by $\mu_Q^2 = t_{\text{max}}$
  $\rightarrow$ starting scale of parton shower evolution
  $\rightarrow$ should be of the order of the scale of the hard interaction
- Powheg and Mc@Nlo now differ in choice of $\mathrm{D}_i^{(\mathrm{A})}$ and μ_Q^2

General NLO+PS matching

$$\langle O\rangle^{\text{NLO+PS}} = \int \mathrm{d}\Phi_B\ \bar{\mathrm{B}}^{(\mathsf{A})}(\Phi_B)\Bigg[\Delta^{(\mathsf{A})}(t_0,\mu_Q^2)\,O(\Phi_B) + \int_{t_0}^{\mu_Q^2}\mathrm{d}\Phi_1\ \frac{\mathrm{D}^{(\mathsf{A})}(\Phi_B,\Phi_1)}{\mathrm{B}(\Phi_B)}\,\Delta^{(\mathsf{A})}(t,\mu_Q^2)\,O(\Phi_R)\Bigg] + \int \mathrm{d}\Phi_R\Big[\mathrm{R}(\Phi_R)-\sum_i \mathrm{D}_i^{(\mathsf{A})}(\Phi_R)\Big]\,O(\Phi_R)$$

$$\begin{aligned}\Delta^{(\mathsf{A})}(t,t') &= \exp\left[-\int_t^{t'}\mathrm{d}\Phi_1\,\mathrm{D}^{(\mathsf{A})}/\mathrm{B}\right]\\ &= \exp\left[-\alpha_s\log^2\tfrac{t}{t'}+\ldots\right]\end{aligned}$$

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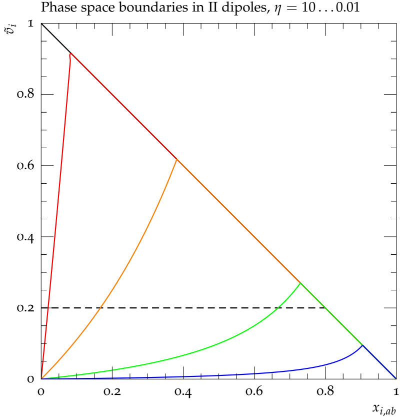
Höche et.al. arXiv:1111.1220

Choice of exponentiated phase space



Real emission phase space

$$\tilde{v}_i = \frac{p_a \cdot k}{p_a \cdot p_b} \qquad x_{i,ab} = 1 - \frac{(p_a + p_b) \cdot k}{p_a \cdot p_b}$$

- restriction in α permits very hard ($x_{i,ab} \to 0$), not too collinear radiation at larger $\tilde{v}_i$
- restriction in $\mathbf{k}_\perp^2 = Q^2\, \tilde{v}_i\, \frac{1-x_{i,ab}}{x_{i,ab}}$ permits only very soft ($x_{i,ab} \to 1$) radiation at larger $\tilde{v}_i$